

# Selective Weakening and Post-tensioning for Retrofit of Non-Ductile R.C. Exterior Beam-Column Joints

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## ABSTRACT

A counter-intuitive “selective weakening” (SW) seismic retrofit strategy for non-ductile RC frame is presented. By focusing on increasing the global displacement and ductility capacity, simple retrofit interventions such as selective weakening of the beams and external post-tensioning of the beam-column joints could change the local inelastic mechanism and result in improved global lateral and energy dissipation capacities. After an overview of the SW retrofit concept, this paper presents the experimental and numerical investigations of SW retrofit techniques for non-ductile RC exterior joints. The experimental results of nine 2/3-scaled exterior joint subassemblies— as-built and SW retrofitted tests are briefly presented. Parameters considered in the tests included the presence of column lap-splice, slab and transverse beams, level of post-tensioning forces and location of beam weakening. Numerical investigation using 3D micro-plane concrete model within smeared fracture mechanics finite-element modelling is demonstrated for SW retrofitted joints. Lastly, a preliminary design procedure is outlined for the design of SW retrofit for exterior beam-column joints. With its economical, non-invasive and low-technology intensity approach, SW retrofit has potential for a wide implementation.

*Keywords:* Selective weakening, seismic retrofit, beam-column joint, reinforced concrete, post-tensioning

## 1. INTRODUCTION

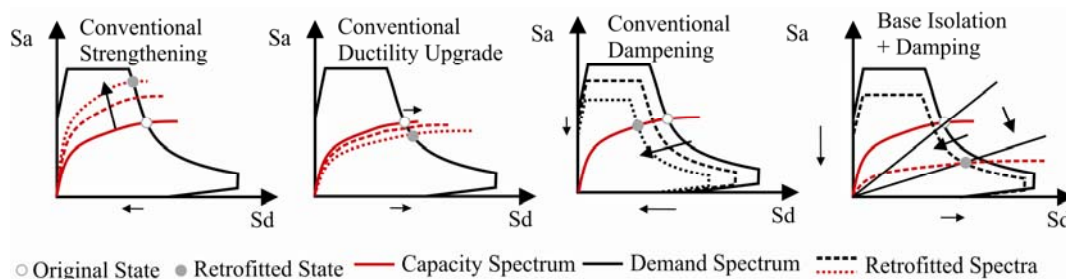
Seismic vulnerability of non-ductile reinforced concrete (RC) buildings in urban seismic zones is a challenging task for earthquake engineering community. Research on the seismic performance of gravity-load-only designed RC frames (prior to modern seismic code) has confirmed beam-column joint failures to be a critical non-ductile collapse mechanism (e.g. (Calvi et al., 2002; Park, 2002). The poor behaviour of joints typical of older construction can be attributed to the inadequate shear reinforcement and details in the joint region, the poor bond properties of plain round bars reinforcements, inefficient anchorage into the joint core and, in a wider sense, the lack of any capacity design considerations. In resolving these seismic deficiencies of non-ductile RC frames, various seismic retrofit solutions have been considerably developed for RC beam-column joints (fib, 2003).

This research is motivated by the need for an economical, low-invasive and low-technology structural retrofit solution that can be widely implemented for non-ductile RC frames. In this contribution, the authors summarise the research on a counter-intuitive “Selective Weakening” (SW) strategy for the seismic rehabilitation of RC frame structures. After a brief introduction on the SW retrofit strategy and techniques, experimental results and numerical studies of SW retrofit for non-ductile exterior RC beam-column joint are presented. This research is part of a large research program on the development of seismic retrofit solutions for multi-story buildings in New Zealand (see acknowledgements).

## 2. SELECTIVE WEAKENING RETROFIT: STRATEGY AND TECHNIQUES

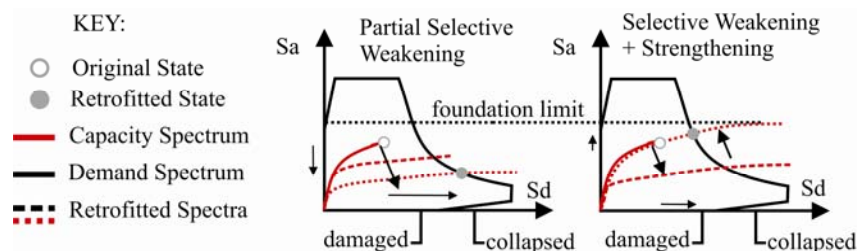
For the retrofit or seismic upgrading of RC frames, global or local strengthening (Fig. 2.1.a) has been and still remains the most popular retrofit strategy. The consequence of such global conventional

strengthening (e.g. adding shear walls) might generate failures elsewhere within the overall structural system such as the foundation, whose strengthening costs and effort are often high and significant. Alternatively, local strengthening of critical elements and components based, for example, on steel, concrete or composite material jacketing can lead to strength and/or ductility upgrade (Fig. 2.1.b), though the cost, labour and technical-intensity of these retrofit techniques might still be a deterrent to their widespread application. Other conventional retrofit strategies involve the reduction of seismic demand by means of supplemental damping (Fig. 2.1.c) and/or use of base isolation systems (Fig. 2.1.d), as these solutions can achieve higher performance levels while being less intrusive. Again, the issue of cost and time/space invasiveness of these common techniques has been the reason for their limited applications on private and ordinary buildings. Conceptually, these retrofit strategies are illustrated in Fig. 2.1. within an Acceleration-Displacement Response Spectrum (ADRS) domain.



**Figure 2.1.** Acceleration-Displacement Response Spectrum (ADRS) illustration of different retrofit philosophies and strategies a) conventional strengthening, b) conventional ductility upgrading, c) added damping, d) seismic base isolation. (CHANGE)

To achieve an improved structural response, the RC frame can instead be “weakened” in order to attract lower seismic force while protecting brittle structural elements such as the joint cores and columns. By changing the inelastic mechanism of the overall frame from a brittle joint shear or column failures to a more ductile beam-sway mechanism relying on beam flexural hinging, higher global deformation capacity can be attained. Conceptually, the SW retrofit strategy is illustrated in Fig. 2.2. for two different retrofit techniques targeting different performance objectives. In a Partial SW, the only intervention involves weakening of the beam to induce flexural plastic hinges (or “the weakest link of the chain” according to the capacity design principles) within the beam-column joint connection (Fig. 2.2.a). In a Full SW, comprising of SW first and followed by strengthening (using post-tensioning) technique, the desired final strength of the system can be controlled, thus protecting the foundations and other brittle structural elements (Fig. 2.2.b).

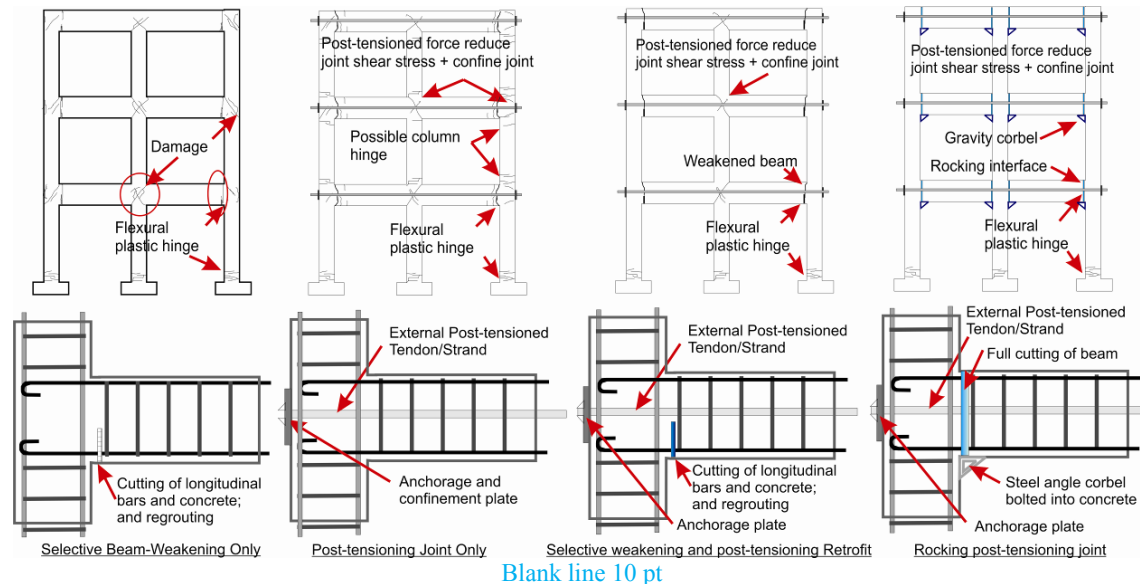


**Figure 2.2.** Acceleration-Displacement Response Spectrum (ADRS) illustration of the Selective Weakening (SW) retrofit strategy: a) Partial SW for collapse prevention, b) SW and strengthening for damage limitation.

Philosophically, the SW retrofit strategy requires somehow a paradigm shift in seismic rehabilitation approaches, in that deformation capacity-demand is prioritised and specific/critical structural (or non-structural) elements can be weakened or strengthened to achieve the overall global objective of non-collapse and limited damage. Fig. 2.3. gives the range of SW retrofit techniques considered in this research, where the first three solutions (Fig. 2.3.a-c) are tested experimentally. Interestingly, the combination of beam-weakening and external joint post-tensioning allows for various design solutions (such as Fig. 2.3.c and 2.3.d) where limited damage performance levels can be attained (as

schematically illustrated in Fig. 2.2.b). By adopting a displacement-based retrofit approach – where damage is correlated to frame deformation, the SW retrofit strategy would become more rationale and clearer.

It is worth mentioning that the concept of weakening itself for seismic retrofit was mentioned in the ASCE-41 (ASCE-SEI-41-06, 2007) while past research at the University of Canterbury have developed the Selective Weakening retrofit for shear-dominated structural wall (Ireland et al., 2007) and hollowcore floor seating connection (Jensen et al., 2007).



**Figure 2.3.** Selective Weakening retrofit techniques for exterior beam column joints: a) Selective beam weakening-only, b) Joint post-tensioning-only, c) Selective beam weakening and joint post-tensioning and d) Rocking post-tensioning joint.

### 3. EXPERIMENTAL INVESTIGATION

#### 3.1. Experimental description

Nine 2/3-scaled non-ductile RC exterior beam joint subassemblies, including three as-built and six SW retrofitted configurations, were tested for this research. Parameters considered in the tests included the presence of column lap-splice, slab and transverse beams, the level of external post-tensioning forces and the location of beam weakening. The prototype joint was designed to represent the worst typical case in pre-1970s construction practice while meeting the requirements of older building codes. The joint core had no transverse reinforcement and the beam longitudinal reinforcements were anchored into the joint using 180 deg. standard hooks (Fig. 3.1.a). All test units had 230mm x 230mm columns and 330mm deep x 230mm wide beams. Plain smooth mild steel reinforcements were used. Displacement-controlled cyclic lateral loading at increasing drift amplitudes (0.1%, 0.2%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5%, 3.0%, 4.0%) with varying column axial load of  $120\text{kN} \pm 4.63F_c$  were used.  $F_c$  was applied lateral load. Only key insights are presented herein with further details available in (Kam, 2010; Kam et al., 2010).

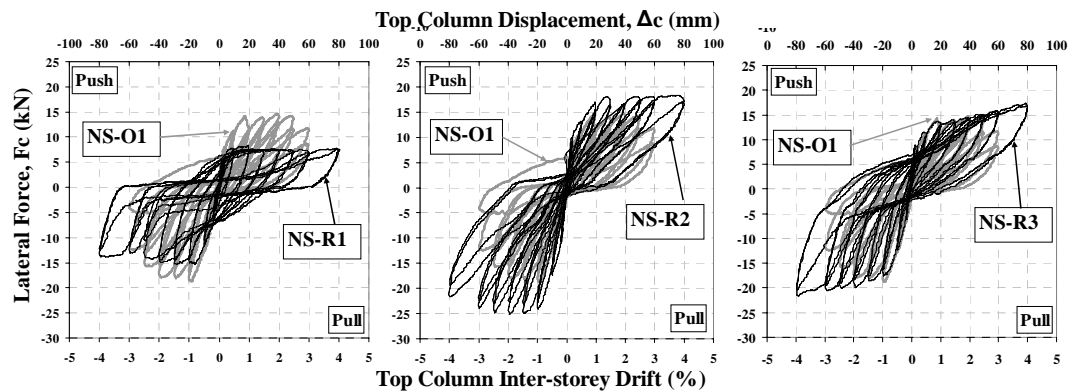
#### 3.2. Weakening-only and post-tensioning-only retrofit solutions

The two intermediate retrofit solutions, namely beam-weakening-only (specimen NS-R1) and external joint post-tensioning-only (specimen NS-R2), demonstrated the feasibility of simple collapse-prevention retrofit. In NS-R1, 50% of the bottom beam longitudinal reinforcements were cut using plate grinder and low-shrinkage mortar was used to re-grout the cut (Fig. 3.1.b). In NS-R2, the retrofit

intervention consisted of a pair of external post-tensioning tendons (7 wire strands, 12.7 mm diameter) with initial prestressing of 60kN (see Fig. 3.1.c). The force-displacement hysteresis curves for both specimens are shown in Fig. 3.2.a and Fig. 3.2.b. NS-R1 retrofit was successful up till 2.5% inter-storey drift before failing (rapidly) in compression anchorage push-out failure. Considering the large hysteresis loops prior to failure, a non-ductile RC frame with such connection would most probably survive collapse prevention or life-safety limit states. For NS-R2, a partial rocking joint behaviour was attained but limited energy dissipation was achieved due to the slipping of the plain-round bars. Column yielding and hinging beyond 2.5% exacerbated the overall behaviour. The column hinging was activated by the increasing post-tensioning contribution and the positive post-yield stiffness. Clearly, a retrofit solution for external joint based on pre-stressing-only, as in NS-R2, would need to consider the associated beam over-strengthening to avoid column hinging.



**Figure 3.1.** a) Joint reinforcing details b) Beam weakening - severing bottom longitudinal bars using plate grinder c) Application of external post-tensioning on the exterior beam-column joint.



**Figure 3.2.** Experimental force-displacement hysteresis curves: a) NS-R1, b) NS-R2, c) NS-R3. Superimposed on all three curves are the force-displacement curves for benchmark specimen NS-O1.

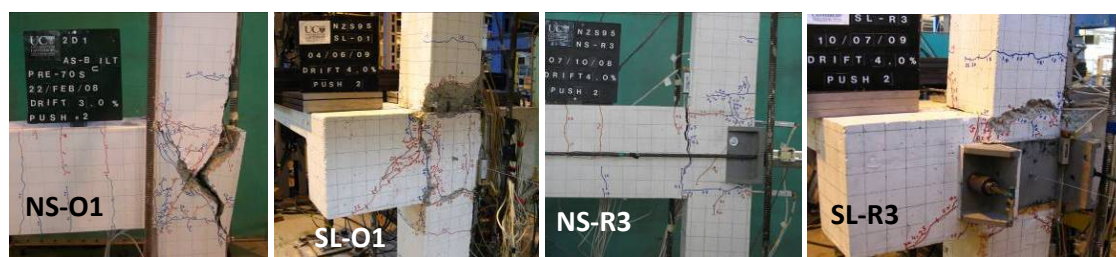
### 3.3. Selective weakening and post-tensioning retrofit solutions

The R3 retrofit scheme involved the combination of a selectively-weakening of the beam and the external post-tensioning of the joint. An initial prestressing force of 20kN was applied. The R3 retrofit solution was implemented in three different as-built scenarios: a) standard as-built joint (NS-R3), b) joint with column lap-splice (S-R3) and c) joint with floor slab and transverse beam stubs (SL-R3). Each as-built scenario had a benchmark specimen and a R3-scheme retrofitted specimen. Fig. 3.3. shows the damage pattern at the end of 4.0% drift cycles for as-built and retrofitted specimens (with and without floor slab). All three R3 retrofitted specimens performed very satisfactorily to 4.0% inter-storey drift, without structural failure, strength degradation or loss of vertical load-carrying capacity.

It can be seen from NS-R3 hysteresis plot (Fig. 3.2.c) that the selective-weakening and post-tensioning retrofit was successful in increasing the deformation and energy dissipation capacities. The beam flexural hinging dominated the inelastic deformation up to 4.0% drift, with cracking concentrated at



the weakened beam section. Minor pinching and in-cycles stiffness degradation in the force-displacement hysteresis were observed due to the bond failure of the bottom beam longitudinal bars. Unlike NS-R2, the selective beam-weakening limited the over-strengthening from the high post-yield stiffness from the unbonded post-tensioned action. The retrofit also limited the joint principal-stresses and joint shear deformation below the threshold of joint diagonal cracking. The force-displacement responses for all three R3-retrofitted specimens were similar, except for an approximately 30% over-strength in the negative beam moment for SL-R3 specimen due to slab flange effect.



**Figure 3.3.** Damage pattern of a) NS-O1, b) NS-R3 c) S-R3 and d) SL-R3.

SL-R3 indicated the importance of the flange-slab effect in the assessment of the beam negative flexural capacity, in order to establish the accurate hierarchy of strength within the beam-column joints. SL-R3 specimen also demonstrated the constructability of the retrofit scheme R3 for realistic joint subassembly and the viability of shear transfer at the weakened beam section (under realistic gravity-seismic shear demand). From the strain-gages data of the specimens with column lap-splices, the beam-weakening and joint post-tensioning retrofit was effective in delaying and preventing complete lap-splice failure. The confinement from the joint post-tensioning prevented the concrete delamination of vertical-cracked concrete due to lap-splice failure.

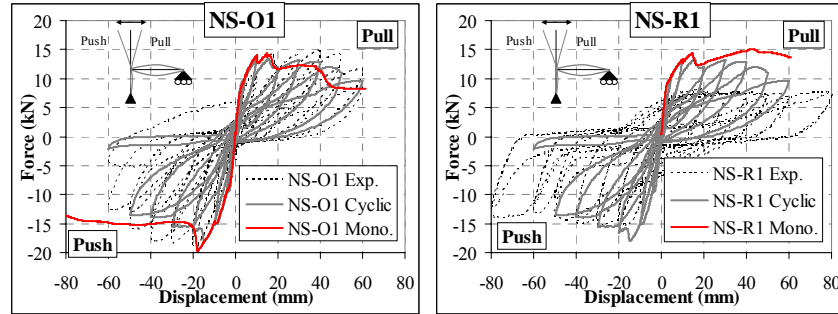
Excessive post-tensioning forces might result in column hinging and/or premature diagonal compressive strut failure, as observed in NS-R1 as well as in prestressed bridge joint tests presented in literature (Priestley et al., 1996). Different weakening location could shift the plastic hinge location away from the joint and provide additional anchorage to the beam-bars, in expense of possibly lower global lateral capacity. The influences of level of post-tensioning forces and location of beam weakening on the retrofit solution R3 are further discussed in (Kam, 2010; Kam et al., 2010).

#### 4. NUMERICAL INVESTIGATION

To better understand the mechanics underlying the retrofitted beam-column joint behaviour, a finite-element (FE) 3D continuum model based on micro-plane concrete model with relaxed kinematic constraint on smeared crack approach (Ožbolt et al., 2001) was used. The FE- model was implemented in MASA3 (Ožbolt, 2008). The longitudinal and transversal reinforcements were modelled using one-dimensional (1-D) truss elements. The bond-slip relationship for plain round bars were modelled using discrete bond element with 1-D constitutive relationship established from pull-out tests. The model for the benchmark joint NS-O1 was developed conjointly with researchers from the University of Stuttgart (Genesio, 2011). For brevity, this paper presents selected numerical results for the NS-O1 and NS-R1 (weakening-only) cases to demonstrate the versatility of the model. Further details of the models and modelling assumptions are available in (Kam, 2010).

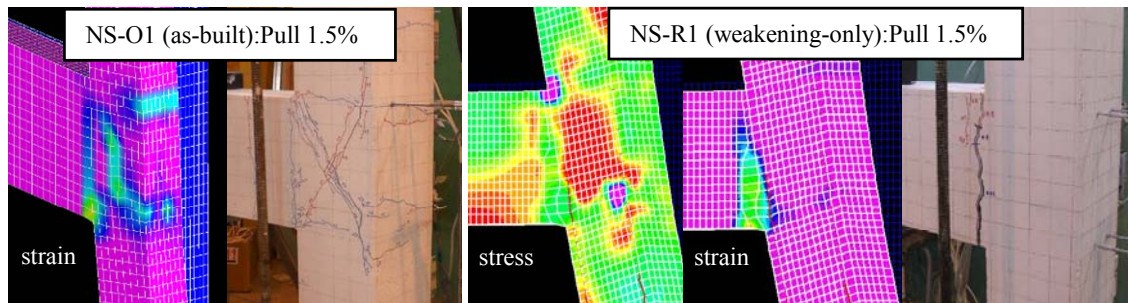
The numerical model was able to capture the joint shear failure and subsequent strength and stiffness degradations of the as-built joint, NS-O1, as observed in the force-displacement hysteresis shown in Fig. 4.1.a. The damage pattern was also accurately predicted by the MASA model (Fig. 4.2a) but the bond slip and associated pinching hysteresis was not fully captured within the current model. More details of the MASA FE modelling and parametric analysis of the non-ductile exterior beam-column joints are available in (Genesio, 2011).

While the FE model predicted correctly the inelastic mechanisms for the retrofitted NS-R1 in both Pull and Push directions, it significantly overestimated the lateral forces in the Pull direction for both monotonic and cyclic analyses. From preliminary analysis of the result, this discrepancy indicated the limitations of the current model in replicating the localised bond-slip and single flexural crack due to the use of plain round bars (see Fig. 3.3.c and Fig. 4.2), while confirming the complexity of the phenomenon. In the Push direction, while the lateral force prediction was within 15% error margin for most points, the MASA model could not capture the significant in-cycles strength degradation due to bond-loss of the plain round bars after the first loading cycles. Nevertheless, similar numerical and experimental NS-R1 ultimate failure modes of anchorage push-out were observed.



**Figure 4.1.** Experimental and numerical force-displacement curves – a) NS-O1 and b) NS-R1.

The refined FE model also generated stress-field maps, which would allow some theoretical validation on the joint shear transfer mechanics within the SW-retrofitted beam-column joints. As shown for NS-R1: Pull 1.5% in Fig. 4.2.b, the uncracked joint was effective in carrying the joint shear stress over a broader band of diagonal compression field despite having no joint stirrups to complete the truss mechanism. The analysis result also indicated that the bond strength of the reinforcements embedded within the joint deteriorates rapidly upon joint diagonal cracking (in NS-O1 model), consistently with the strain readings from the experimental results.



**Figure 4.2.** Predicted (strain and stress of FE elements) and observed cracking pattern of NS-O1 and NS-R1.

## 5. QUICK RETROFIT DESIGN PROCEDURE

Herein, a quick retrofit design procedure is outlined to illustrate the ease of designing for SW retrofit of exterior beam-column joints and RC frames. The prerequisite for the retrofit design is a realistic seismic assessment of the as-built beam-column joint hierarchy of strength and elements' capacities. It is assumed that the required base-shear,  $V_{b\text{-req}}$  for the retrofitted frame can be derived using force-based or displacement-based seismic assessment procedures (fib, 2003). This requires the corollary assumption that the inelastic mechanism of the SW-retrofitted frame is changed to beam-sway flexural hinging as postulated in SW retrofit strategy. Given a  $V_{b\text{-req}}$ , using an equilibrium approach, the required lateral force capacity per beam-column connection or per storey can be determined. Design expressions given in Eqns. 5.1. to 5.4. can therefore be used to approximate the lateral column force,

$F_c$  of SW retrofitted beam-column joints. As a simplification, the contributions from the non-prestressed and prestressed reinforcements are evaluated separately. For beam-weakening only retrofit, the  $M_b = M_{b,rc}$  while for post-tensioning with or without beam-weakening,  $M_b = M_{b,rc} + M_{b,pt}$ .

$$F_c = \frac{M_{col,bf}}{H'_c} = \phi_{slab} M_b \left( \frac{H_c}{2L_b H'_c} \right) \quad (5.1)$$

$$M_{b,rc} = A_s f_y (j_{rc} d) \quad (5.2)$$

$$M_{b,pt} = \phi_o T_{pt} (j_{pt} d) \quad (5.3)$$

where  $\phi_{slab}$  is a global over-strengthening factor due to slab flange effect;  $A_s$  and  $f_y$  are the steel area and yield strength of the beam longitudinal reinforcements;  $d$  is the effective depth of the beam (beam depth minus concrete cover);  $j_{rc}$  and  $j_{pt}$  are the approximate level arm coefficients for prestressed and non-prestressed reinforcements, and are taken to be 0.85 and 0.35 respectively; and  $\phi_o$  is the prestressing force over-strengthening factor (due to elongation of the tendon at beam centreline). Tentatively for design,  $\phi_{slab}$  and  $\phi_o$  are taken to be 1.5 and 2 respectively. The suggested values for  $j_{pt}$  and  $\phi_o$  are assuming the location of the tendon at the centre of the beam and relatively low level of post-tensioning forces ( $T_{pt} < 40\%$  of yield strength of the tendons).  $A_s$  with and without selective weakening are  $157\text{mm}^2$  and  $314\text{mm}^2$  respectively while  $f_y$  is taken to be  $330\text{MPa}$  based on test specimens' steel coupon tests.  $H'_c$ ,  $H_c$ , and  $L_b$  are the distance from beam top-face to column contra-flexural point, the inter-storey height and half the beam-span respectively.

To ensure the joint panel and column are protected, the calculated equivalent column moment corresponding to yielding of the beam,  $M_{col,bf}$  must be compared to the equivalent column moments corresponding to joint shear failure, column hinging and other possible failure mechanisms. The inelastic mechanism can be determined by comparing the hierarchy of strength of all failure modes within a equivalent column moment ( $M$ ) versus column axial load ( $N$ ) interaction diagram (Pampanin et al., 2007; Kam, 2010). The maximum joint shear stress,  $v_{jh}$  that can be sustained prior to diagonal joint cracking can be calculated by solving the principal tensile stresses equation:

$$p'_c, p'_t = \frac{f_v + f_h}{2} \pm \sqrt{\left( \frac{f_v - f_h}{2} \right)^2 + v_{jh}^2} \quad (5.4)$$

where  $p'_c$  and  $p'_t$  are the diagonal cracking limit states for principal compression and tensile stresses; and  $f_v$  and  $f_h$  are the vertical and horizontal (post-tensioning) axial stresses. (Priestley et al., 1996) suggested  $p'_t \approx 0.29\sqrt{f'_c}$  MPa and  $p'_c \approx 0.3f'_c$  MPa as conservative limit states.

**Table 5.1.** Comparison between experimental and quick design lateral load capacities.

Test Unit	Experimental 2.0% Lateral Load (kN)		Quick Design Lateral Capacity (kN)		Ratio of Exp-to-Design Load/Capacity <sup>1</sup>	
	Pull (+ve)	Pull (-ve)	Pull (+ve)	Pull (-ve)	Pull (+ve)	Pull (-ve)
NS-R1	7.3	14.1	7.0	14.0	1.04	1.01
NS-R2	16.9	25.7	27.4	27.4	0.62	0.94
NS-R3	14.7	19.5	11.5	18.5	1.28	1.05
NS-R4	12.2	20.5	8.5	14.7	1.44	1.39
S-R3	14.4	20.4	11.5	18.5	1.25	1.10
SL-R3	19.1	26.9	14.3	23.1	1.34	1.16

Some of the design constants ( $\phi_{slab}$ ,  $\phi_o$ ,  $j_{rc}$  and  $j_{pt}$ ) can obviously be more accurately evaluated by a refined sectional analysis. For quick design purposes, the tentative recommended values yield reasonable comparison to the experimental results (given in Table 5.1. above) but further parametric studies are required to confirm the design constants. The experimental values were taken from the 1<sup>st</sup> cycles of the 2.0% drift as per typical seismic code limit state specification. The calculated capacity of

NS-R2 was inaccurate as the beam-column joint capacity was limited by column hinging mechanism. For other specimens, it can be observed that the simplistic approach shown above is sufficient for a preliminary sizing (how much to weaken and to post-tension). For more complete treatment of the analytical evaluation and design of SW retrofit for beam-column joints refer to (Kam, 2010).

## 6. CONCLUSIONS

This paper has presented selective-weakening (SW) and joint post-tensioning as feasible seismic retrofit strategy and techniques for non-ductile exterior beam-column joint. By changing the inelastic mechanism via selective weakening of desired failure mode, higher deformation capacity can be achieved and collapse/soft-storey can be prevented. From experimental investigation, it was shown that by a) selectively weakening the beam of exterior joints (NS-R1); b) upgrading the beam-column joints using external pre-stressing (NS-R2); or both a) and b) (retrofit scheme R3), the joint panel zone was protected and an improved inelastic mechanism was activated. Fracture mechanics-based FE models were demonstrated in modelling the complex as-built and retrofitted joints. Both experimental and numerical investigations have indicated the importance of selective beam-weakening, post-tensioning forces and consideration for slab and post-tensioning over-strengths. A quick retrofit design procedure was outlined to illustrate the simplicity of the SW retrofit concept. It is expected that SW retrofit will be soon part of the toolbox available to structural engineers when tackling the problem of seismic rehabilitation.

## ACKNOWLEDGEMENTS

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## REFERENCES

- ASCE-SEI-41-06. (2007). Seismic rehabilitation of existing buildings. ASCE/SEI, Reston, Va.
- Calvi, G. M., Magenes, G., and Pampanin, S. (2002). Experimental test on a three storey RC frame designed for gravity only *Proc. of 12th European Conference of Earthquake Eng.*, London, UK. Paper No 727
- fib. (2003). *Seismic assessment and retrofit of reinforced concrete buildings: State-of-the-art report*, fib Bulletin no. 24, International Federation for Structural Concrete (fib), Lausanne, Switzerland.
- Genesio, G. (2011). Seismic response of RC beam-column exterior joints before and after retrofit (in preparation), PhD dissertation, University of Stuttgart, Stuttgart, Germany.
- Ireland, M. G., Pampanin, S., and Bull, D. K. (2007). Experimental investigations of a selective weakening approach for the seismic retrofit of r.c. walls. *NZSEE Conference 2007*, Palmerston North, NZ. Paper No. 16
- Jensen, J., Bull, D. K., and Pampanin, S. (2007). Experimental investigation of existing hollowcore seating connection: Seismic behaviour pre and post retrofit intervention. *NZSEE Conference 2007*, Palmerston North, NZ. Paper No. 12
- Kam, W. Y. (2010). Performance-based selective weakening seismic retrofit for R.C. structures (in preparation), PhD dissertation, University of Canterbury, Christchurch.
- Kam, W. Y., Pampanin, S., and Bull, D. K. (2010). A summary of test results for selective weakening and post-tensioning for retrofit of non-ductile R.C. exterior beam-column joints. *NZSEE 2010 Conference*, Wellington, N.Z. Paper No. 29
- Ožbolt, J. (2008). MASA3 - Finite element program for 3D nonlinear analysis of concrete and reinforced concrete structures Institut für Werkstoffe im Bauwesen, University of Stuttgart, Stuttgart, 53 pp.
- Ožbolt, J., Li, Y., and Kožar, I. (2001). Microplane model for concrete with relaxed kinematic constraint. *International Journal of Solid and Structures*, **38**:16, 2683-2711.
- Pampanin, S., Bolognini, D., and Pavese, A. (2007). Performance-based seismic retrofit strategy for existing reinforced concrete frame systems using fiber-reinforced polymer composites. *ASCE J. of Composite Constr.*, **11**:2, 211-226.
- Park, R. (2002). A summary of result of simulated seismic load tests on reinforced concrete beam-column joints, beams and columns with substandard reinforcing details. *J. of Earthquake Eng.*, **6**:2, 147-174.
- Priestley, M. J. N., Seible, F., and Calvi, G. M. (1996). *Seismic design and retrofit of bridges*, John Wiley & Sons Inc., NY.